DEVELOPMENT OF GRAPHICAL INDICES FOR DISPLAYING LARGE SCALE BUILDING ENERGY DATA SETS

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ABSTRACT

Graphs are an effective way of displaying quantitative and statistical information. Unfortunately, only a few studies have systematically looked at presenting building energy data in forms which are both informative and easy to comprehend. Recent advancements in computing, including the development of sophisticated graphing packages and powerful desktop computers have made the concept of graphical indices more timely than ever before.

In this paper, graphical indices are developed and used to analyze several years of hourly data (20,000 to 30,000 data points) collected from LoanSTAR sites. These indices are meant to be efficient displays that present data in specific graphic

building's energy consumption behavior need to be quickly and accurately viewed so that buildings can be compared with one another. The purpose of this paper is to show how graphical indices can be used to help a building energy analyst view large amounts of hourly building energy consumption data in order to quickly and efficiently analyze the data, check for errors, or establish time and temperature related trends over a large period of time. The objective is to demonstrate the use and effectiveness of the graphical indices on the data collected from an Engineering Center.

THE LOANSTAR PROJECT

The LoanSTAR (Loans To Save Taxes And Resources) program was established in 1988 as an eight-year, $98.6 million revolving loan program to fund energy conserving retrofits in state and local government buildings (Verdict et al. 1990). Additional information about the program can be found in Claridge et al. (1991, 1992). A major portion of the effort in this program has been devoted to measuring energy savings and developing a statewide end-use database.

LoanSTAR Data Processing and Management

Several months prior to installing retrofits in a building, data acquisition systems (DASs) are installed to monitor energy consumption. Data collected both before and after the retrofits help to determine the savings from the retrofit. Data are retrieved weekly via modem from onboard memory in the data loggers located in the building. The raw ASCII data are then downloaded and merged with National Weather Service weather data from 50 sites and LoanSTAR weather data from 7 sites. After

LoanSTAR data processing routines are public domain. They are used to poll the loggers and perform several data quality checks such as setting hi/low limits, character conversion, adding decimal date stamps, replacing missing data with a default (-99), and plotting the data for the Inspection Plot Notebooks for review by the LoanSTAR staff. Further information about the LoanSTAR data processing can be found in Lopez and Haberl (1992a, 1992b).

The number of sites participating in the LoanSTAR program has increased over the years. Depending on the extent of monitoring, a building may have a few or many data monitoring channels. Figure 1 shows the rise in the number of data monitoring channels and the growth in the size of the database as more sites were included in the program.

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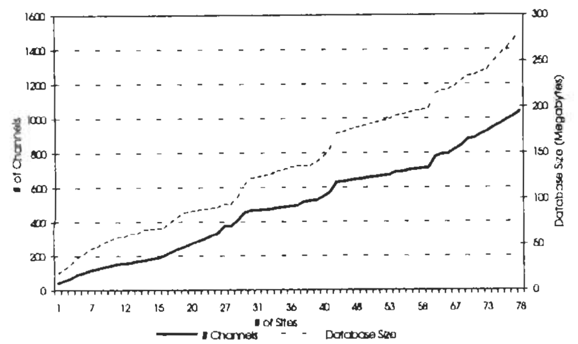

Figure 1. Data monitoring channels and size of the LoanSTAR database.

LITERATURE REVIEW

When dealing with large data sets, one is typically faced with performing statistical data analysis. Statistical data analysis is useful if the relationship between variables is well defined. Statistical analysis can then show the strength of the relationship. However, if the analyst does not know what to expect from the data then it becomes neccessary to view the data to establish relationships in order to perform further analysis. Graphical data analysis is relatively new as compared to numerical and other statistical data analysis procedures. Many statistical analysis procedures were developed in the early twentieth century while procedures for graphical data analysis have been on the rise since the 1960's as access to computer graphics software has increased (Cleveland 1985).

The purpose of any graphic presentation is to allow the reader to easily and accurately decode information that is encoded by the graph's author. However, the information encoded within graphs is not always easily decoded or correctly decoded by the viewer of the graphs. Sometimes, improper graphic presentation may lead to misleading results. At present, many types of graphs are used in the scientific literature to display data. Most common of these are time-series graphs, line graphs, scatter plots, horizontal and vertical bar charts, pie charts, and most recently, 3-D surface plots and contour density plots.

Few building energy researchers have systematically looked at how to present large amounts of building energy data with regard to graphical perception. There are several seminal references on graphics, including: Cleveland (1985), Tufte (1983, 1990), and Tukey (1977, 1988). These works provide a very detailed look at the problems associated with commonly used graphs and provide a comprehensive list of principles that should be followed to enhance the ability of a graph to show the structure of the data.

A survey of the ASHRAE Transactions from 1954 to 1992 showed that most graphs in the 1950's, 1960's, and 1970's were usually hand-drawn by draftsmen. Obviously a lot of thought went into each graph before they went to the draftsman because changes were expensive and time consuming. Three dimensional (3-D) graphs first appeared in the ASHRAE literature in the late 1970's. Although 3-D graphs present a tremendous amount of data in a compact graph, it is generally difficult to spot exact details. A 3-D graph uses "small multiples" (Tufte 1983) by positioning the slices such that the viewer makes comparisons of relative positions of the slices at a glance without visual interruption. A 3-D graph is an effective method of plotting three or four variables that takes advantage of the mind's spatial abilities[1].

Graphs and charts used in building energy data generally follow the trends laid out in other fields of science. Several works have contributed significantly to the development of graphs of building energy data, including: Christensen (1984), Christensen and Ketner (1986), Haberl et al. (1988a, 1988b, 1989a, 1989b, 1992, 1993a), Bronson et al. (1992), and the Electric Eye software package (Supersymmetry 1992).

A well researched review of graphical display developments is presented by Christensen (1984), who traced the development of the 3-D graphical plots to Olgyay's climatic contour plots and Milne's 3-D graphs (Olgyay 1963; Milne and Yoshikawa 1978; ref. Christensen 1984). Christensen also proposed the use of Energy Maps (EMAPS - colored contoured plots) as an extension of the 3-D surface plots (Christensen 1984; Christensen and Ketner 1986).

Haberl et al. (1988a) used 3-D graphics to display simulation results from the DOE-2 computer program. They used two sets of rotational and tilt angles; 45° tilt and rotation angles to better view

[1]The three variables used in the building energy analysis include the day-of -the-year along one axis and hour-of-the-day along a perpendicular axis that form an X-Y plane. The energy use is then the height of the surface above the X-Y plane. A fourth variable can be added by coloring or shading the surface plot.

daily profiles and 15° tilt and 80° rotation angles to better locate day-of-occurrence. The paper showed that annual 3-D profiles of hourly data can be very useful for analyzing hourly energy consumption data. Also, the 3-D surface plots significantly reduced the voluminous hourly data output.

Haberl et al. (1988a, 1988b, 1989a, 1989b, 1993a) and Bronson et al. (1992) used 3-D comparative plots to view small differences between the simulated data and the measured data for non-weather dependent loads. Axis alignment or juxtaposition[2] was used to facilitate comparison. In this paper juxtapositioning and juxtapaging[3] are used for comparison across panels and across succeeding pages.

For weather dependent loads, carpet plots have been used to detect different trends between DOE-2 simulations and measured consumption (Haberl et al. 1992). A more general purpose carpet plot was shown by Cleveland (1985) to be capable of detecting non-linearity in data using a technique called brushing. This work builds on the carpet plotting concept of displaying many variables on a single page. It also uses separate symbols to differentiate two or more data sets across multiple axes. The original labeling proposed by Cleveland has also been simplified to make the graph easier to read.

The Electric Eye (Supersymmetry 1992) is an advanced proprietary software package. It can be used to analyze data in many forms from simple 2-D to advanced 3-D graphics. This proprietary software provides many graphic utilities including rotating, translating, zooming, scaling, and sectioning along any axis. Other proprietary packages have also been developed with similar features including PVWAVE (PVWAVE 1993), IDL (IDL 1993), and Voyager (Voyager 1990). These packages have varying degrees of graphical sophistication. However, none have been developed with the same objective as the displays of building energy data developed in this paper.

[2]Juxtaposition refers to horizontal and /or vertical axes alignment.

[3]Juxtapaging refers to the same data plotted with different graphs in similar locations on succeeding pages. For example, Figure 2 and Figure 3 are juxtapaged.

GRAPHICAL PERCEPTION

When a graph is constructed, quantitative information is encoded in it. In order to extract this information, the analyst has to use his/her judgment and/or experience to decode the hidden information. An efficient graph is one that does not confuse the analyst and makes the decoding process simple and uncomplicated. The decoding process involves graphical perception. An understanding of graphical perception is necessary in order to generate graphics that invoke the most efficient perception tasks. Experimentation with different forms of graphs have shown that certain graphical perception tasks are more effective than others (Cleveland 1985). The following lists the graphical perception tasks from the (1) most effective to the (7) least effective:

1. Position along a common scale
2. Position along an identical, non-aligned scale
3. Length
4. Angle and Slope
5 Area
6. Volume
7. Color hue, Color Saturation, Density

The graphs that are developed in the sections that follow attempt to apply these perception tasks. These graphical indices are used to display weather dependent and non-weather dependent or schedule dependent trends. Typically, one type of graphical index displays information which may not be readily seen by another index. A combination of these graphical indices helps detect events and trends that are difficult, if not impossible, to perceive when viewing one graph separately. Often this is necessary to quickly and efficiently analyze data, check for errors, or establish time and temperature related trends over a large period of time. Additional information about the detailed construction of these graphs is shown in Abbas (1993).

GRAPHICAL INDICES OF BUILDING ENERGY DATA

In this section the graphical indices that have been developed by Abbas (1993) are used to analyze building energy consumption data. The graphical indices are further enhanced with widely used energy consumption indices to facilitate comparison across buildings. Examples of energy indices are whole-building electricity consumption as W/ft^2, whole-building chilled water and steam/hot water consumption as Btu/ft^2-h. Data from the Zachry

Engineering Center (ZEC) on the Texas A&M University campus are used to present the concepts.

Figure 2 shows the multi-year 3-D surface plots for the whole-building electricity consumption for the ZEC. Each panel shows one year of data with the most recent year at the top. The 3-D surface plots are oriented so that the extreme left end of the horizontal axis is the first day of the year (Jan. 1^{st}), the right side is the last day of the year (Dec. 31^{st}), and the axis into the page represents the hour-of-the-day.

A normalized index (W/ft^2) is used to show the energy consumption to facilitate comparison across sites. Z-axis gridlines are also included to aid in judging the consumption levels. The ZEC was retrofitted with a VAV system that became fully operational in March, 1991. One can see that the peak consumption before the retrofit remained above 4 W/ft^2 and then dropped to below 4 W/ft^2 after the retrofit. The unoccupied period electricity use of the building before the retrofit was also high, and dropped after the retrofit as well. This is due to the large number of air handling units (AHU) that were operated 24 hours a day to condition the building, the 24-hour operation of the Cray super computer, and the large number of PCs and other office equipment used by the students at all times. After the retrofit in March, 1991, the base load dropped by about 0.5 to 1 W/ft^2, an appreciable drop considering the size of the building (324,400 ft^2). This drop in consumption is due largely to the conversion of the constant volume AHU fan motors to variable speed motors. This drop can be clearly seen in Figures 2 and 3.

From the consistent 3-D hourly profiles, it seems that this building follows a more or less defined schedule with consumption increasing in the morning and decreasing in the evening. The weekday/weekend effect can also be seen from the alternate peaks and valleys throughout the year. There are a few short periods of missing data each year. Seasonal dips in consumption occurring at approximately the same time each year can also be seen. These are the periods when the university was closed for holidays and the building was only partially occupied. Most pronounced are the Christmas holidays during the beginning and at the end of each year, the one-week spring break in March, and the two-week breaks at the end of the spring (May) and summer semesters (August).

Figure 3 shows Box, Whisker and Mean (BWM) plots for the same data. Box plots were first developed by John Tukey at Princeton (Cleveland 1985). Each box and whisker symbol efficiently displays the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles. The box extends from the 25^{th} (first quartile) to the 75^{th} (third quartile) percentile, while the whiskers extend from the top of the box (75^{th} percentile) to the 90^{th} percentile and from the bottom of the box (25^{th} percentile) to the 10^{th} percentile. The median (50^{th} percentile) is marked somewhere inside the box with a single cross hatch. Values less than the 10^{th} percentile and greater than the 90^{th} percentile are marked as pluses, which lie blow or above the whiskers.

Several features that could not be seen with the hourly 3-D surface plots can now be seen more accurately using the weekly BWM plots. For instance, the rise and drop in consumption as the university closes and re-opens (spring break, week 11; May, week 19; August, week 33; December, week 51), the peaks and the minimum consumption level (4^+ W/ft^2 and 2 W/ft^2), and the drop in peak and the minimum consumption level due to the retrofit that occurred during March, 1991. However, it is interesting to note that the peak consumption during the fall semester, 1992 was slightly higher than the fall semester 1991. This is probably due to the addition of personal computers and other office equipment.

Each BWM symbol represents one week of data from Sunday through Saturday.[4] In the BWM plot there is an interesting relation between the medians and the means.[5] As can be seen, the means, joined by the dotted line, are mostly well above the medians but become closer to the medians for the weeks when the building was closed due to the holidays during Christmas and semester breaks. The reason for this is the reduced electricity use during the occupied hours of the break. During normal operation the building is operated at 3 - 4 W/ft^2 for approximately ten hours during weekdays including a few hours of operation at peak loads during the late

[4] This means that missing data does not show in the BWM plot if the missing periods are less than seven days in length. Therefore, even one day's consumption shows up as a BWM plot symbol for that week.

[5] The mean is the point at which the connecting line crosses the box and whisker. The median is the cross-hatched within the box.

morning and early afternoon hours. Therefore, in one week, consisting of 168 hours, the occupied period amounts to approximately 50 hours or less than 30%. The median, which is the 50th percentile, therefore, invariably falls in the unoccupied period data and hence is located near the bottom of the box. The mean represents the average hourly consumption for the week and is influenced by the magnitude of the occupied load and therefore is located well above the median. In other words, at the ZEC those periods when the mean is above the median indicate that the building is mostly occupied.

During holidays, there are only a few occupied hours. The building is mostly operated at unoccupied loads and the means are not influenced as much by the magnitude of the occupied consumption load and, hence, lie closer to the medians. The fewer the occupied hours and the smaller the rise in occupied period load, the closer the means are to the medians. For instance, during Christmas breaks, means and medians are almost the same, but are some distance apart during the 47th week (Thanksgiving) when the building had two holidays that would have normally been weekdays.

Since the 52-week BWM plot presents weekly data, information in hourly data is lost. In Figure 4 the electricity consumption is displayed using BWM statistics for each hour for all days of the week, weekdays and weekends, for 1992. Each hourly BWM symbol, therefore, is generated using 365 data points for all seven days, 261 data points for weekdays and 104 data points for weekends. In the all days case, the medians are located higher than the means because the building is occupied about 60% of the days (i.e., 210 school days per year), and so the median (50th percentile) during working hours invariably falls during weekdays. However, during early morning and late evening hours, the means and medians both approach a common mid-point within the interquartile range, because the building is mostly unoccupied during these hours, regardless of weekdays, weekends, or holidays.

The middle panel in Figure 4 shows the consumption for weekdays only. In this plot, the lengths of the interquartile ranges are considerably shorter, indicating a more consistent consumption pattern, which is expected. The points below the 10th percentile show holiday consumption[6] during weekdays, which also pull the means down.

The bottom panel in Figure 4 shows consumption during weekends only. The nearly flat profile indicates that the building remains unoccupied during weekends. The points mostly below the 10th percentile show the weekends during Christmas holidays.

Figure 5 shows the coincident cumulative frequency plots for the whole-building and Motor Control Center (MCC) electricity consumption for the pre-retrofit[7] and the post-retrofit periods. The whole-building electricity consumption data are first sorted from maximum to minimum and then plotted against the coincident MCC electricity consumption. The approximate 100 kW drop in peak whole-building electricity consumption due to the retrofit accounts for only 58% of the apparent 170 kW reduction in peak electricity use for the MCC. This difference is probably due to a take-back effect of increased PCs and miscellaneous loads. It is also worth noting that during the pre-period the spread in the MCC consumption is narrower (CV = 0.024) compared to that in the post-period (CV = 0.079), a characteristic of a VAV system.

Figures 6 shows the BWM-scatter plots of the hourly pre-post chilled water consumption. This figure was designed to display the pre-post chilled water consumption's dependency on ambient temperature. The upper panels show the hourly scatter plots while the bottom panels show the same data as the BWM plots for 5°F temperature bins. During the pre-retrofit period, it is clear that the building consumed about 12 Btu/ft^2-h even at temperatures as low as 20°F. This is due to the inefficient mixing that occurs with constant volume dual duct systems in the absence of an economizer cycle. The VAV retrofit appears to have cut the chilled water consumption almost in half for temperatures below 65°F. At temperatures around 80°F, the building seemed to approach a limiting capacity of about 22 Btu/h-ft^2 even as ambient temperature rose to 100°F or more. This was due to fouled chilled water coils in the air-handling unit. The chilled water coils were re-tubed shortly after the

[6]Holidays were not grouped with weekends because holiday scahedule may vary from building to building.
[7]There were a lot of missing data and only about 7000 hours of data are available for the pre-retrofit period.

retrofit in 1991. The lower right panel, where both pre-retrofit and post-retrofit mean-lines are drawn, shows that there has been a significant drop in consumption across all temperature bins due to the VAV retrofit. The consumption falls to approximately 5 Btu/h-ft^2 at lower temperatures and steadily rises at higher temperatures to approximately 20 Btu/h-ft^2, versus 22 Btu/h-ft^2 during the pre-retrofit period. The change point temperature that indicates maximum cooling moved from 80°F in the pre period to 90°F in the post.

Figure 7 shows a carpet plot matrix where both pre-retrofit and post-retrofit chilled water consumption are plotted with separate symbols against four weather variables. The dependency of chilled water consumption on ambient temperature and specific humidity is similar, that is, greater consumption at higher ambient temperatures and specific humidity. The pre-retrofit consumption (triangles) at temperatures between 50°F and 75°F is clearly higher than the consumption (pluses) during the post period. At temperatures above 75°F, the pre and the post-period consumption overlap, forming a very dark cluster. The chilled water consumption seems to be independent of both the solar radiation and wind speed.[8]

The carpet plot in Figure 8 was developed to highlight any relationships between whole-building electricity, motor control center, lights and receptacles (L&R), chilled water, and hot water consumption. The second graph in the first row shows that the whole-building electricity use versus MCC electricity use has two clouds of data points. These clouds suggest that the reduction in whole-building electricity consumption is largely due to reduction in MCC electricity consumption.

The fifth graph in the fourth row from the top shows that chilled water use versus HW use also has two data clusters.[9] The upper cluster (triangles) suggests a linear relation between the chilled water and HW consumption during the pre-retrofit period. In constant volume systems, in the absence of an economizer both the cold and hot air streams are mixed to attain the desired supply temperature. In contrast, the lower cluster (post retrofit) shows that very little hot water is used during periods when there is a high chilled water consumption.

The HW versus CHW graphs also indicate the potential savings of implementing an economizer cycle during the heating season to cool the interior of the building. In the post-retrofit period, the chilled water consumption remains around 2,000 kBtu/h, with a corresponding hot water consumption of 1,400 kBtu/h or more. This is because even at cooler temperatures when the outer zones in the building may require heating, the interior zones are still being cooled with chilled water when they might be cooled with economizers. The second graph in the fourth row, where CHW is plotted against MCC, shows a stronger relationship between CHW and MCC in the post-period. This is expected because VAV systems are supposed to vary with ambient conditions as does the CHW load.

DISCUSSION

It has been shown that the graphical indices can show important features of a building's energy consumption behavior. The 'per square foot' indices used for the graphs are used to facilitate comparison across buildings. Some of these indices are more powerful than others in helping to determine specific characteristics about a building's energy use. Following is a brief discussion of the value and limitation of each type of graphical index.

3-D Surface Plots

The 3-D surface plots can be used to qualitatively show the peak consumption, the valleys, periods of missing data, weekday/weekend effects, seasonal/semester effects, and the 24-hour profiles. However, a judicious choice of scales and orientation is needed in order to show all the aspects.

52-Week BWM Plots

In contrast to the 3-D surface plots, where actual collected data is plotted, statistical BWM plots show the data in a more concise form. Connecting the means across box and whisker plots is an added feature to the plots. Several features of the BWM plots seem to be related to the energy consumption behavior of the building. For instance, the relative position of the mean and the median is related to the operating schedule, the length of the box (the interquartile range) is related to the spread of the data or possible on/off operation of the HVAC system, the points above the whisker show the data values at peak consumption (highest 10%), and the points below the

[8] Unfortunately, some of the separation of the data may be due to the fact that weather station instrumentation was changed-out between the pre and post periods.

[9] HW use versus chilled water use can also be seen in fifth row fourth graph.

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whisker show data value at unoccupied load (lowest 10%).

24-Hour BWM Profile Plots

The 24-hour BWM profile plots are useful to see the distinction between the weekday and weekend profiles. After sorting for weekday and weekend, the 24-hour BWM plots can quickly let the viewer see if any unaccounted-for holidays remain in the weekday days. For the ZEC these days showed up as continuous 24-hour periods below the 10th percentile.

Pre-Post Scatter and BWM Plots

The pre-post scatter and BWM plots are useful for investigating changes in the weather dependent loads, such as the chilled water and the hot water consumption. The use of combined scatter and BWM plots provide the viewer with both a detailed view of the individual hourly data points and a statistical view of the data points at discrete bins. The effectiveness of the retrofit is clearly shown by viewing the bin by bin shift in data points from the pre to the post period. The mean-line in the BWM plots shows the average change in energy consumption with the change in the ambient temperature. The mean-line is also a good indicator of whether or not to choose a linear or change-point linear curve fit to model a building. An interquartile range that is too large may be indicating the need for an additional sort prior to binning, for example on/off operation or weekday/weekend operation. Last but not least, the superposition of the mean lines in the bottom right panel shows the savings due to the retrofit by the shift in the mean consumption within each temperature bin.

Coincident Cumulative Frequency Plot

The coincident cumulative frequency plots are very useful to see the effect of the retrofit on the whole-building and MCC electricity consumption. Data problems can also be identified with these plots.

Pre-Post Carpet Plot Matrix

A carpet plot matrix is useful for investigating the dependency of energy consumption on multiple weather variables. These plots are enhanced by adding histograms and by using separate symbols for pre-retrofit and post-retrofit data. Separate symbols used for the pre-post periods assist in the visual determination of the effect of a retrofit (CV system versus VAV system) and enhance the ability to view changes across all variables. The juxtaposed histograms enhance the effectiveness of the plot by displaying the density of data points. Also, because all the weather variables are plotted against one another, comparisons across sites become more meaningful because the analyst can easily view differences in weather across cities. Changes in the weather patterns between pre and post periods can be determined as well.

The pre-post carpet plot matrix which juxtaposes energy consumption channels to one another is also a useful plot. However, the exact meaning of the relationship displayed requires an understanding of HVAC system types and interactions. These plots can show details that may not be seen easily from any other graph. Relationships between the whole-building and MCC electricity consumption, between the chilled water and hot water consumption, and between electrical and thermal consumption are easily viewed with these matrices.

CONCLUSIONS

In a large program like LoanSTAR many aspects of a building's energy consumption behavior need to be quickly and accurately viewed. It was demonstrated that graphical indices can be used to help a building energy analyst view large amounts of hourly building energy consumption data in order to quickly and efficiently analyze the data, check for errors, or establish time and temperature related trends over a large period of time. It was shown in the ZEC's case that the 3-D surface plots can be used to show the drop in electricity consumption due to the VAV retrofit as well as the seasonal variation due to the semester schedule. The weekly BWM plots show week-by-week occupancy of the building by the relative positions of the medians and means. The 24-hour BWM plots show the hourly profiles for all days, weekdays, and weekends. These plots are also useful to identify holidays that fall during weekdays. The pre-post BWM-scatter plots show the temperature dependency and the shift in energy consumption due to the retrofit in small 5°F temperature bins. In addition, these plots give an indication of how the building can be modeled and the lengths of the boxes indicate whether the building has an on/off operation. Finally, the carpet plot with separate pre and post symbols provides for a closer analysis of the dependency of one variable on several others.

The graphical indices described in this paper were developed to visually display historical building energy consumption. Unfortunately, these static plots sometimes pose visual problems such as too many data points in a small space. Already some work has been accomplished on methods that use animation or time sequencing (Belur et al. 1992, Haberl et al. 1993b). Future work should be directed towards both improved static displays, which could further resolve the problem of data overlapping, and dynamic displays, which could be presented in time periods of lengths that do not over-burden the analyst.

There is also room to enhance a few of the indices. For instance, in the current carpet plots, the histograms encompass all the data points (pre and post-retrofit periods) within one bin and, therefore, it is not possible to tell the distribution of the pre-post data points in each bin. A carpet plot with separate pre-post histograms would provide additional insight into the distribution of the two variables.

The indices developed are in use by the staff of the LoanSTAR program and serve as the foundation for the LoanSTAR Data Summary Notebook. The effectiveness of these indices would also be enhanced through additional interviews with building operators, administrators, energy managers, and analysts to see which indices they prefer and what information can be extracted from these indices.

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REFERENCES

Abbas, M. 1993. *Development of graphical indices for building energy data.* Masters thesis. Mechanical Engineering Department Texas A&M University.

Belur, R., R. J. Sparks, and J. S. Haberl. 1992. *Documentation manual for MKMOV*: version 0.91β. Texas Engineering Experimentation Station. Texas A&M University.

Bronson, D. J., S. B. Hinchey, J. S. Haberl, and D. L. O'Neal. 1992. A procedure for calibrating the DOE-2 simulation program to non-weather-dependent measured loads. *ASHRAE Transactions* 98(1): 645.

Christensen, C. 1984. Digital and color energy maps for graphic display of hourly data. *Proceedings of the 9th Annual Passive Solar Conference,* Columbus Ohio. (September).

Christensen, C., and K. Ketner. 1986. Computer graphics analysis of class B hourly data. *Proceedings of the 11th National Passive Solar Conference* Boulder, CO. (June).

Claridge, D., J. Haberl, K. Kissock, and J. Wu. 1991. *The Texas LoanSTAR Program: Early measured savings.* Energy System Laboratory. Report # ESL-PA-91/09-01.

Claridge, D., J. Haberl, R. Sparks, R. Lopez, and K. Kissock. 1992. *Monitoring commercial building energy data: Reporting the results.* Energy System Laboratory. Report # ESL-PA-92/01-01.

Cleveland, W. S. 1985. *The elements of graphing data.* Wadsworth and Brooks/Cole Advanced Books and Software, Pacific Grove, CA.

Haberl, J. S., Mac Donald, M., and A. Eden. 1988a. An overview of 3-D graphical analysis using DOE-2 hourly simulation data. *ASHRAE Transactions* 94(1).

Haberl, J. S., and E. J. Vajda. 1988b. Use of metered data analysis to improve building operation and maintenance: Early results from two federal complexes. *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings,* Asilomar, CA (August-September).

Haberl, J. S., L. K. Norford, and J. V. Spadaro. 1989a. Diagnosing building operational problems: Intelligent systems for diagnosing operational problems in HVAC systems. *ASHRAE Journal* (June).

Haberl, J. S., and P. S. Komor. 1989b. *Investigating an analytical basis for improving commercial building energy audits: Results from a New Jersey Mall.* Center for Energy and Environmental Studies. Princeton University, NJ.

Haberl, J. S., D. Bronson, and D. O'Neal. 1992. *An evaluation of the impact of using measured weather data versus TMY weather data in a DOE-2 simulation of an existing building in central Texas.* ESL Report. Texas A&M University.

Haberl, J. S., D. Bronson, S. Hinchey, and D. O'Neal. 1993a. Graphical tools to help calibrate the DOE-2 simulation program. *ASHRAE Journal* (Jan.).

Haberl, J. S., R. Belur, and K. Kissock. 1993b. Improving the paradigm for displaying complex building energy consumption data. *Proceedings of the ASME-ACES International Solar Energy Conference,* Washington, D.C. (April).

IDL. Interactive Data analysis Language. 1993. Research Systems Inc. Boulder, CO 80303.

Lopez, R. and J. Haberl. 1992a. *Data management in the LoanSTAR program.* Energy System Laboratory. Report # ESL-PA-92/02-11.

Lopez, R. and J. Haberl. 1992b. *Data processing for monitored building energy data.* Energy System Laboratory. Report # ESL-PA-92/04-08.

Milne, M., and S. Yoshikawa. 1978. Solar-5, an interactive computer-aided passive solar building design system. *Proceedings of the 3rd National Passive Solar Conference,* Vol. 3, Newark, Delaware.

Olgyay, V. 1963. *Design with climate: Bioclimatic approach to architectural regionalism.* Princeton University Press, Princeton, NJ.

PVWAVE. 1993. Visual Numerics. Boulder, CO.

SAS. 1989. *Statistical Analysis System.* SAS Institute, Cary, NC.

Supersymmetry. 1992. *Electric eye.* Supersymmetry, U.S.A, Inc. Plantersville, Texas.

Tufte, E. R. 1983. *The visual display of quantitative information.* Graphic Press, Cheshire, Connecticut.

Tufte, E. R. 1990. *Envisioning information.* Graphic Press, Cheshire, Connecticut.

Tukey, J. W. 1977. *Exploratory data analysis.* Addison-Wesley Publishing Co. Reading, MA.

Tukey, J. W. 1988. *The collected work of J. W. Tukey. Vol. 5, graphics; 1965 - 1985.* Wadsworth Publishing. Monterey, CA.

Verdict, M., J. S. Haberl, D. Claridge, D. O'Neal, W. Heffington, and W. Turner. 1990. *Monitoring $98 million in energy efficient retrofits: The Texas LoanSTAR Program.* Energy System Laboratory. Report # ESL-PA-90/08-01.

Voyager. *Voyager Users manual.* 1990. Lantern Corporation. Clayton, MO 63105.

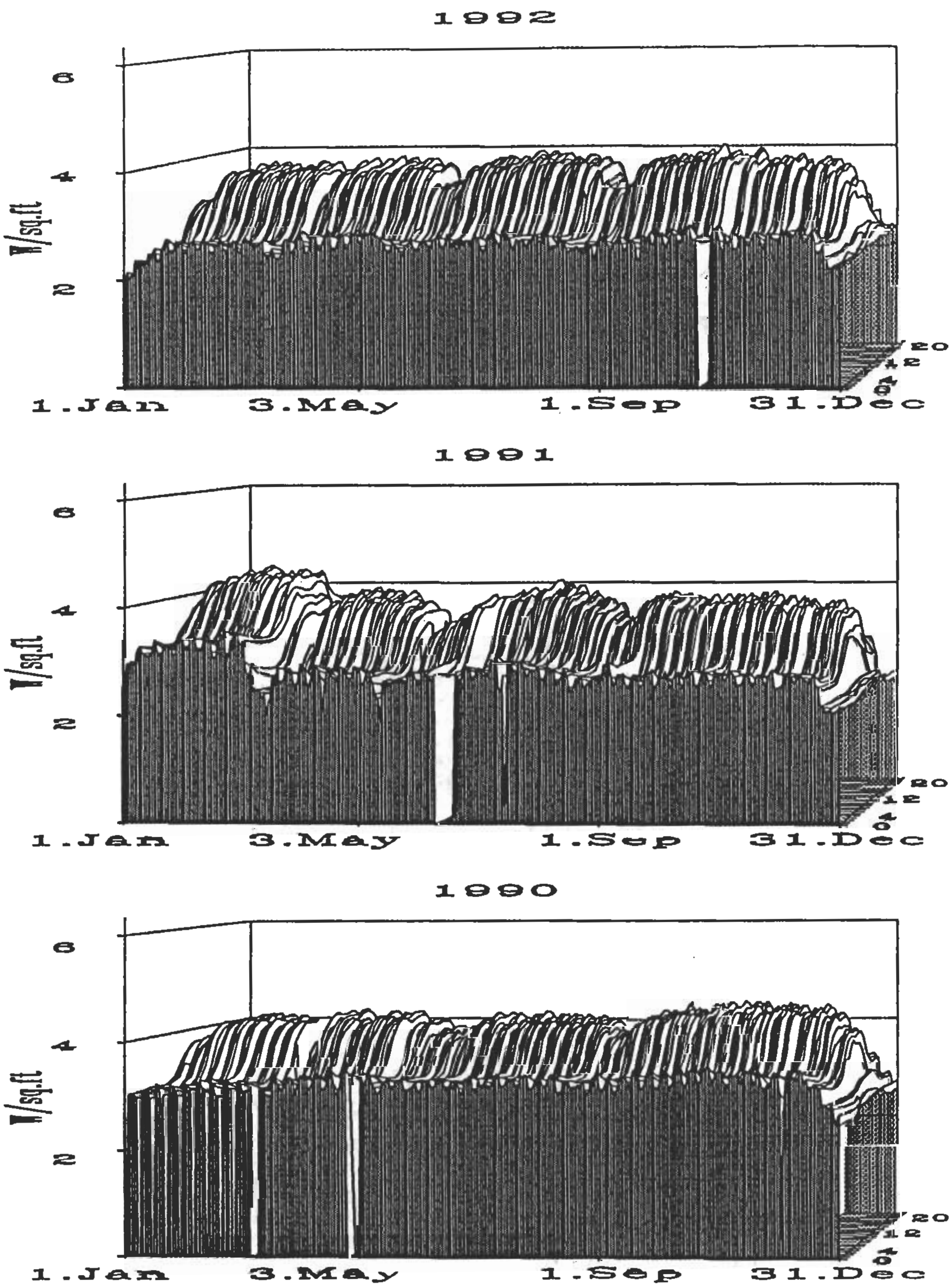


Figure 2. Annual, juxtaposed 3-D surface plots for three years of whole-building electricity consumption for the period 1990 though 1992.

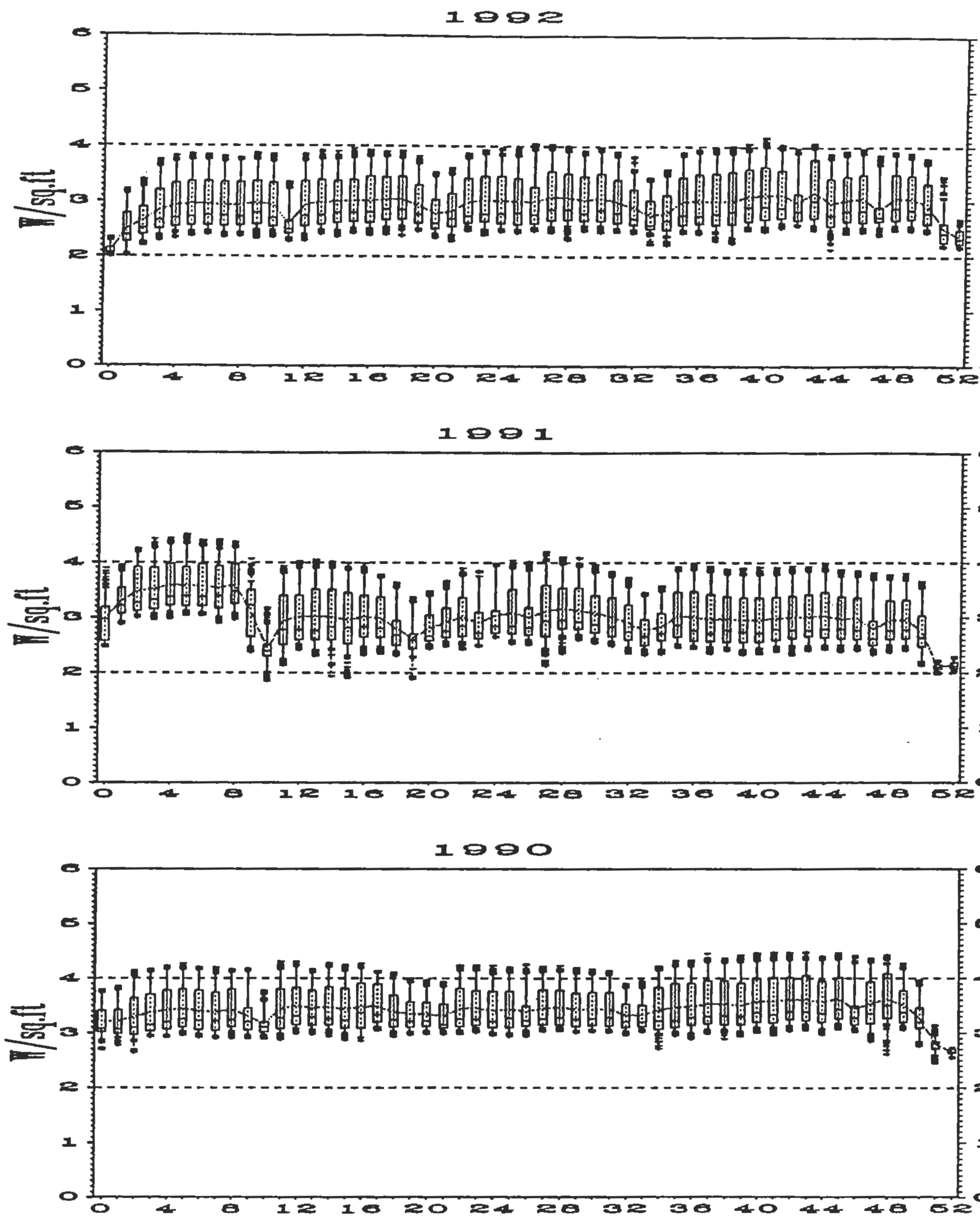


Figure 3. Juxtaposed, Fifty-two week BWM plots of the whole-building electricity consumption for the period 1990 through 1992.

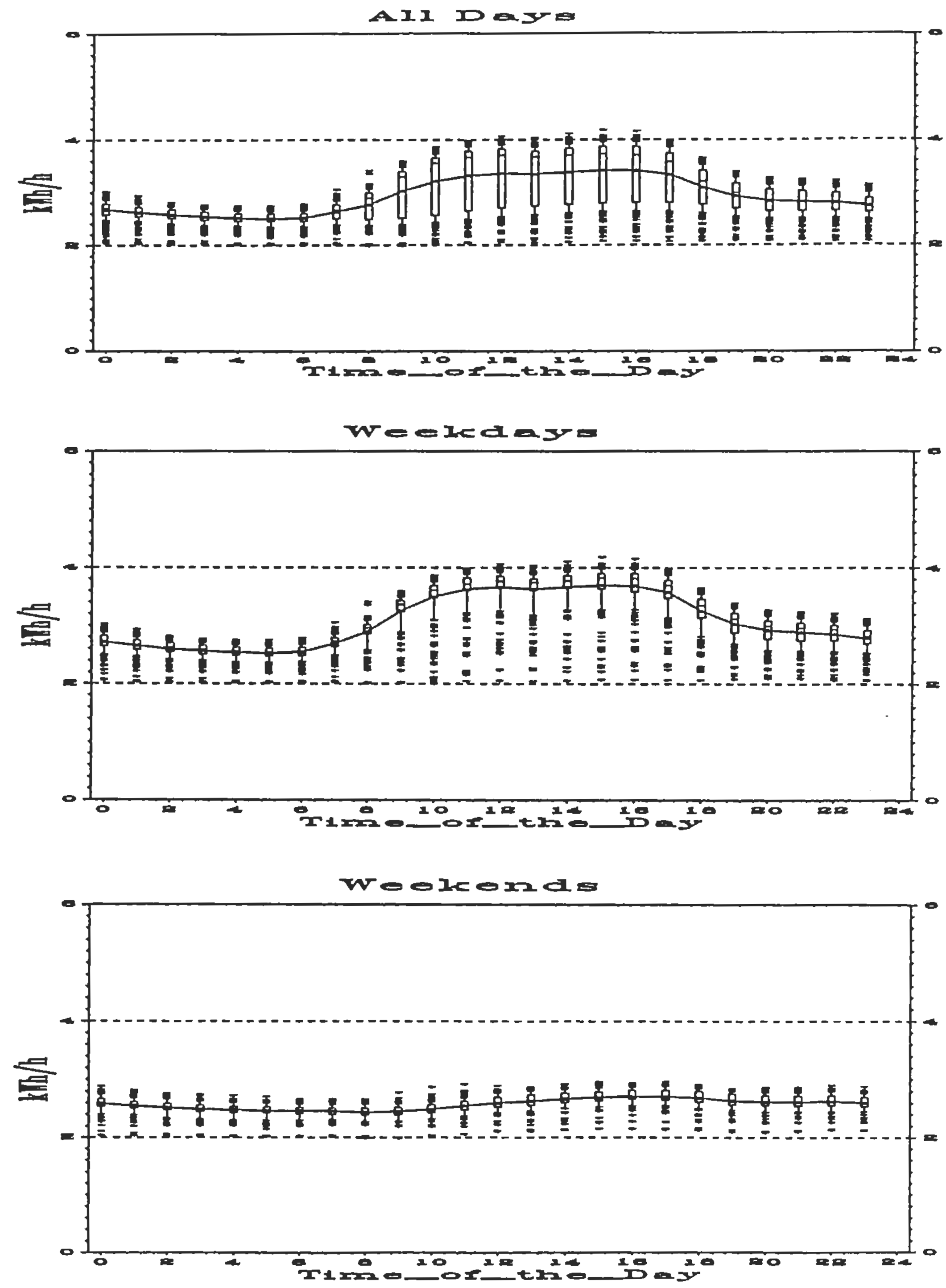
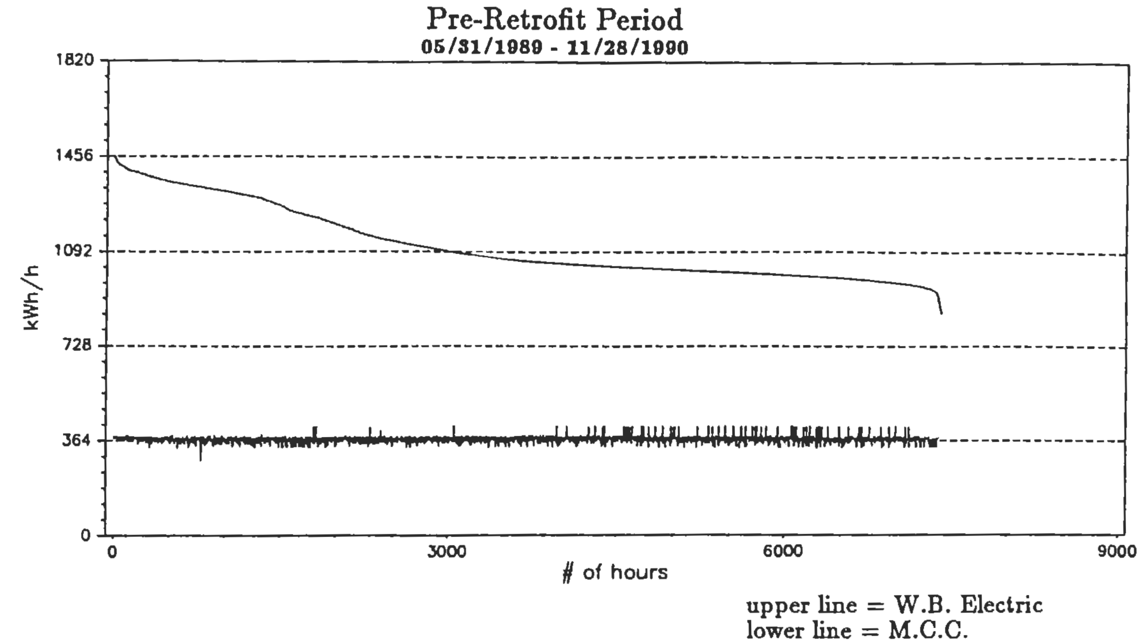


Figure 4. 3-panel BWM plots showing daily, weekday, and weekend day type profiles for 1992.



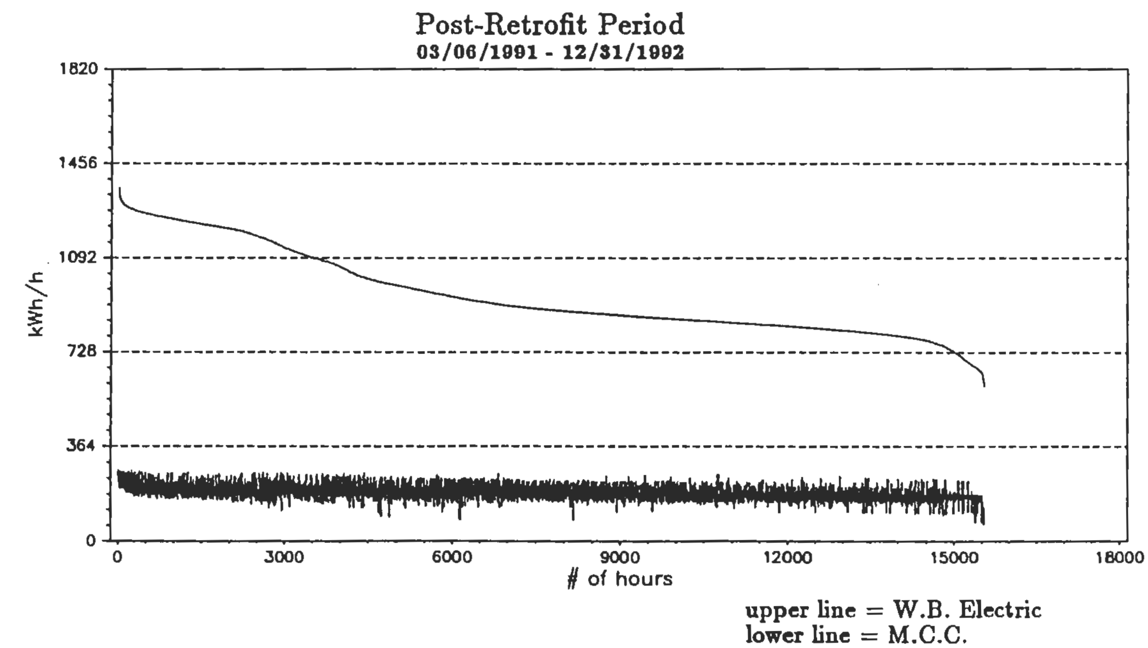


Figure 5. Coincident cumulative frequency plots for the pre-post whole-building and MCC electricity consumption.

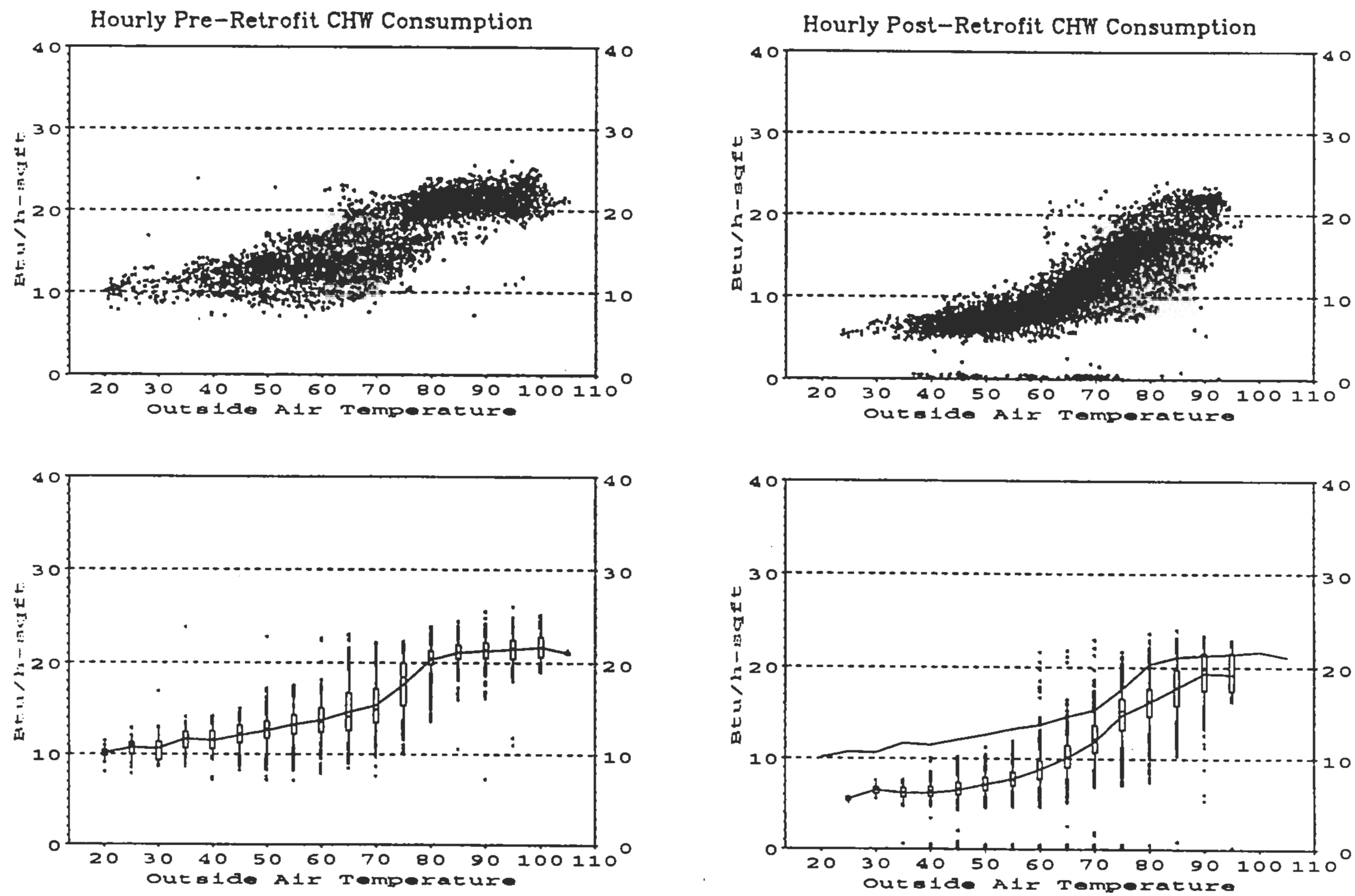


Figure 6. Scatter and BWM plots of the hourly, pre-post whole-building chilled water consumption.

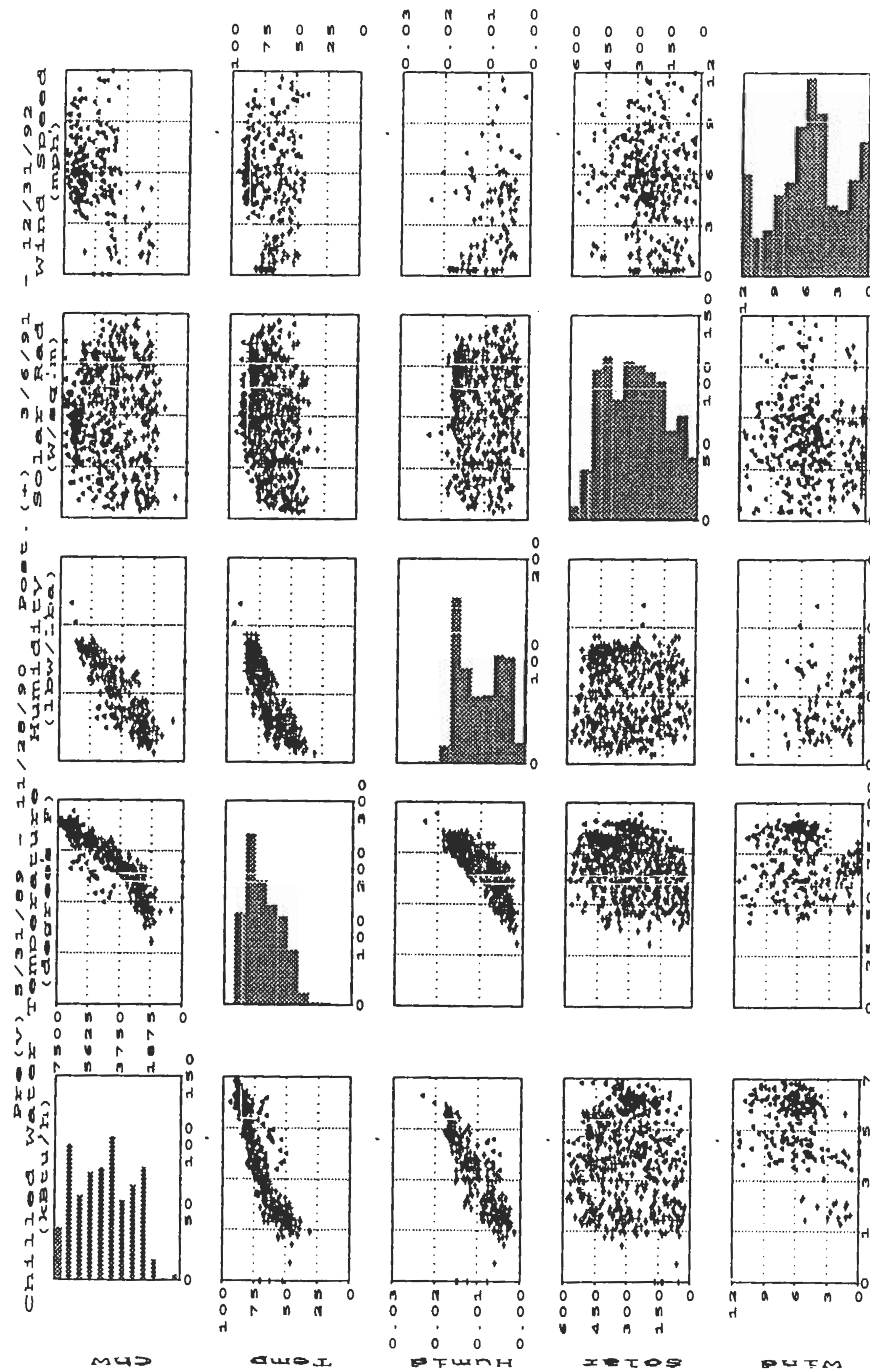


Figure 7. Carpet plot matrix with superimposed histograms for the whole-building chilled water consumption and weather variables using daily averaged data.

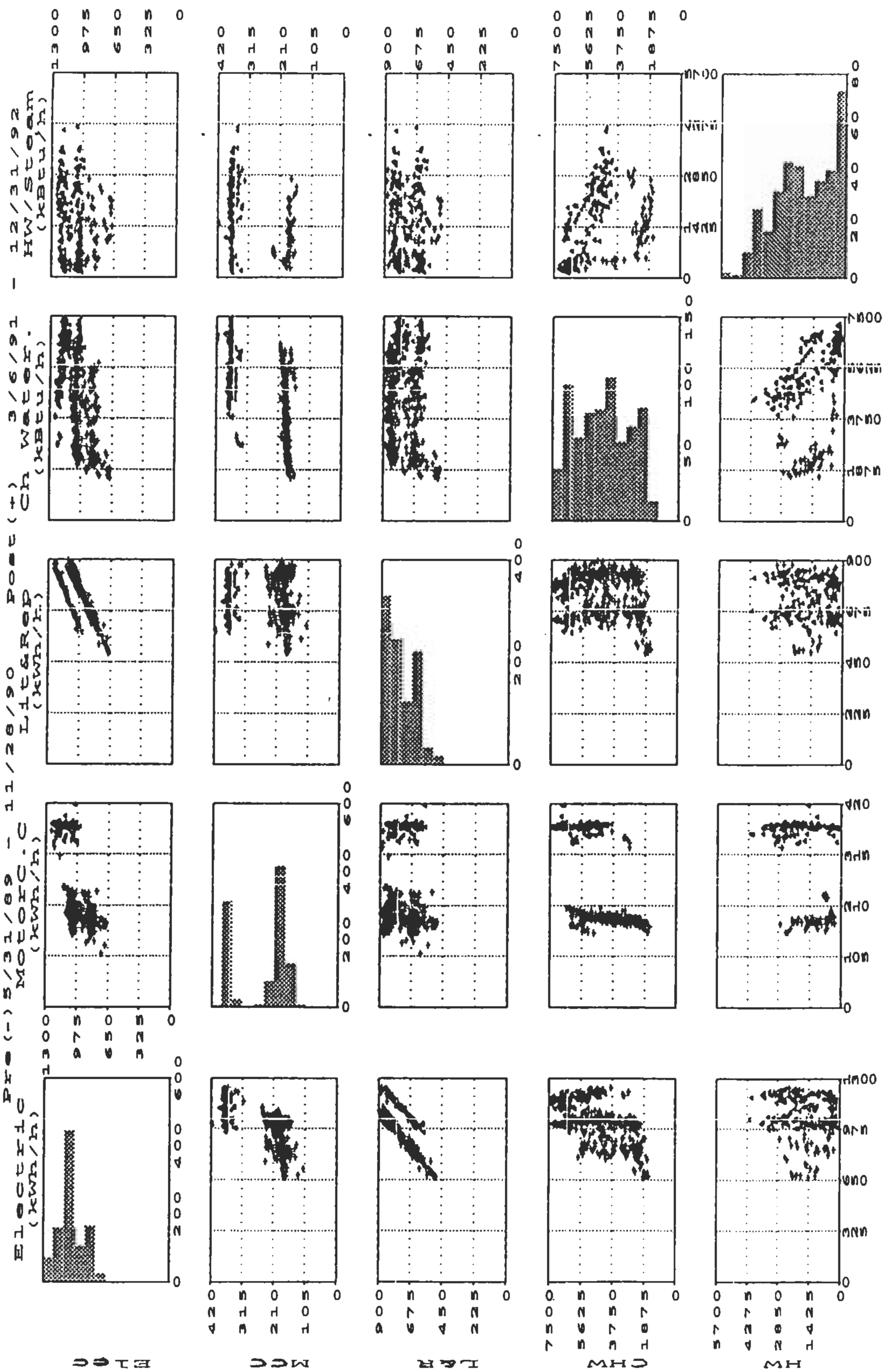


Figure 8. Carpet plot matrix using averaged daily data for all the energy consumption channels.